

Hadron Physics with Anti-protons: The $\overline{\text{P}}\text{ANDA}$ Experiment at FAIR

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Abstract

The theory of Quantum Chromo Dynamics (QCD) reproduces the strong interaction at distances much shorter than the size of the nucleon. At larger distance scales, the generation of hadron masses and confinement cannot yet be derived from first principles on basis of QCD. The $\overline{\text{P}}\text{ANDA}$ experiment at FAIR will address the origin of these phenomena in controlled environments. Beams of antiprotons together with a multi-purpose and compact detection system will provide unique tools to perform studies of the strong interaction. This will be achieved via precision spectroscopy of charmonium and open-charm states, an extensive search for exotic objects such as glueballs and hybrids, in-medium and hypernuclei spectroscopy, and more. An overview is given of the physics program of the $\overline{\text{P}}\text{ANDA}$ collaboration.

1 Introduction

The fundamental building blocks of QCD are the quarks which interact with each other by exchanging gluons. QCD is well understood at short-distance scales, much shorter than the size of a nucleon ($< 10^{-15}$ m). In this regime, the basic quark-gluon interaction is sufficiently weak. In fact, many processes at high energies can quantitatively be described by perturbative QCD. Perturbation theory fails when the distance among quarks becomes comparable to the size of the nucleon. Under these conditions, in the regime of non-perturbative strong QCD, the force among the quarks becomes so strong that they cannot be further separated. As a consequence of the strong coupling, we observe the relatively heavy mass of hadrons, such as protons and neutrons, which is two orders of magnitude larger than the sum of the masses

of the individual quarks. This quantitatively yet-unexplained behavior is related to the self-interaction of gluons leading to the formation of gluonic flux tubes connecting the quarks. As a consequence, quarks have never been observed as free particles and are confined within hadrons, i.e. the baryons containing three valence quarks or mesons containing a quark-antiquark pair.

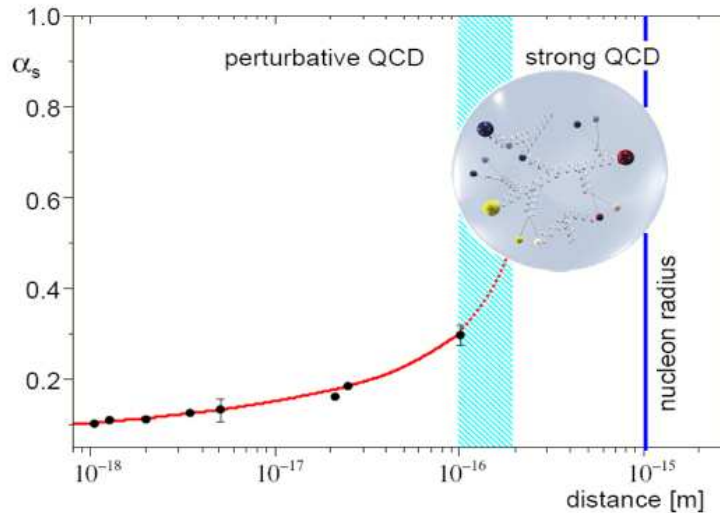


Figure 1: *The strong coupling constant, α_s , as a function of the distance scale. Towards larger distances, QCD becomes non-perturbative, and gives rise to spectacular phenomena such as the generation of hadron masses.*

The physics program of the $\overline{\text{P}}\text{ANDA}$ (anti-Proton ANnihilation at DArmstadt) collaboration [1] will address various questions related to the strong interactions by employing a multi-purpose detector system at the High Energy Storage Ring for anti-protons (HESR) of the upcoming Facility for Anti-proton and Ion Research (FAIR) [2]. The $\overline{\text{P}}\text{ANDA}$ collaboration aims to connect the perturbative and the non-perturbative QCD regions, thereby providing insight in the mechanisms of mass generation and confinement. For this purpose, a large part of the program will be devoted to

- charmonium spectroscopy;
- gluonic excitations, e.g. hybrids and glueballs;
- open and hidden charm in nuclei.

In addition, various other physics topics will be studied with $\overline{\text{P}}\text{ANDA}$ such as

- the hyperon-nucleon and hyperon-hyperon interactions via γ -ray spectroscopy of hypernuclei;
- CP violation studies exploiting rare decays in the D and/or Λ sectors;
- studies of the structure of the proton by measuring Generalized Parton Distributions (Drell-Yan and Virtual-Compton Scattering), "spin" structure functions using polarized anti-protons, and electro-magnetic form factors in the time-like region.

2 $\overline{\text{P}}\text{ANDA}$ physics topics

The key ingredient for the $\overline{\text{P}}\text{ANDA}$ physics program is a high-intensity and a high-resolution beam of antiprotons in the momentum range of 1.5 to 15 GeV/c. Such a beam gives access to a center-of-mass energy range from 2.2 to 5.5 GeV/c² in $\overline{p}p$ annihilations. In this range, a rich spectrum of hadrons with various quark configurations can be studied as is illustrated in Fig. 2. In particular, hadronic states which contain charmed quarks and gluon-rich matter become experimentally accessible.

2.1 Charmonium Spectroscopy

The level scheme of lower-lying bound $\overline{c}c$ states, charmonium, is very similar to that of positronium. These charmonium states can be described fairly well in terms of heavy-quark potential models. Precision measurements of the mass and width of the charmonium spectrum give, therefore, access to the confinement potential in QCD. Extensive measurements of the masses and widths of the $1^- \Psi$ states have been performed at e^+e^- machines where they can be formed directly via a virtual-photon exchange. Other states, which do not carry the same quantum number as the photon, cannot be populated directly, but only via indirect production mechanisms. This is in contrast to the $\overline{p}p$ reaction, which can form directly excited charmonium states of all quantum numbers. As a result, the resolution in the mass and width of charmonium states is determined by the precision of the phase-space cooled beam momentum distribution and not by the (significantly poorer) detector resolution.

The combination of the much better mass resolution with the ability to detect hadronic final states which have up to two orders of magnitude higher branching fractions than - for instance - the $\gamma\gamma$ decay channel will permit high-precision investigations of charmonium states. The need for such a tool becomes evident by reviewing the many open questions in the charmonium

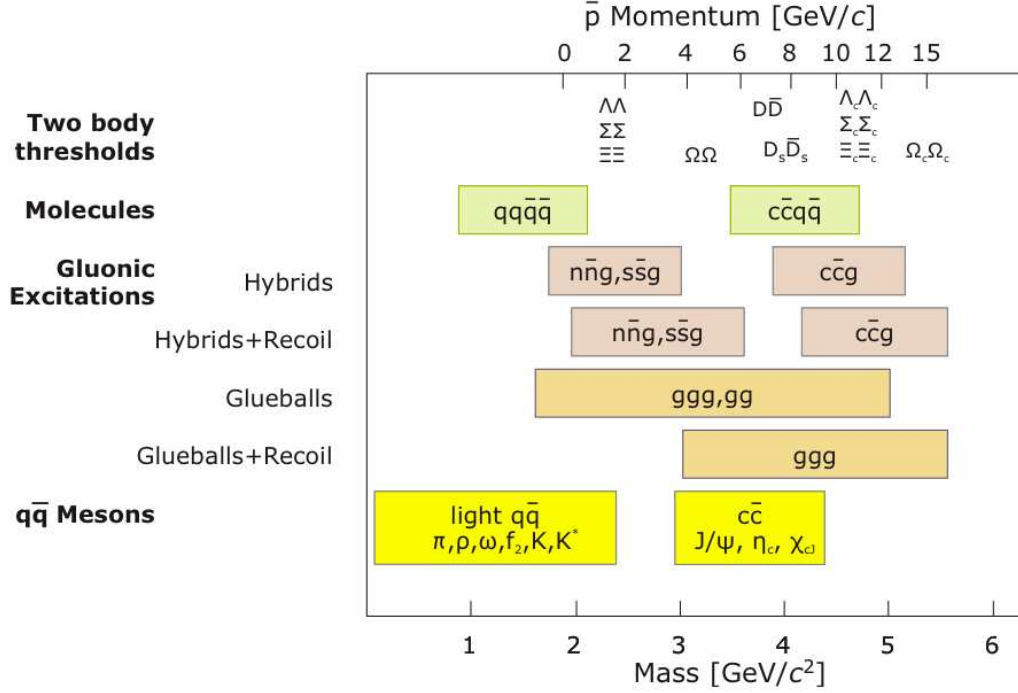


Figure 2: An overview of the various quark and gluon configurations of hadrons and their corresponding mass range. The \bar{P} ANDA experiment will exploit masses up to 5.5 GeV/c² in antiproton-proton collisions, thereby having access to glueballs, charmed hybrids, and charmed-rich four-quark states.

sector. For instance, our knowledge of the ground state, η_c , is surprisingly poor. The existing data [3–7] do not present a consistent picture, and only a small fraction of the total decay width has been measured via specific decay channels. Furthermore, radial excitations, such as the η'_c , which was only recently discovered [8], are not simple recursions of the ground state, as was observed in the hadronic decays of the Ψ states. Another open question is the spin-dependence of the $q\bar{q}$ potential. For this, a precise measurement of the mass and decay channels of the singlet-P resonance, h_c , is of extreme importance. The available data for the h_c are of poor precision [9, 10]. Due to the narrow width, $\Gamma < 1$ MeV, of this state, only $\bar{p}p$ formation experiments will be able to measure the width and perform systematic investigations of the decay modes. Finally, our understanding of the states above the $D\bar{D}$ threshold is very poor and needs to be explored in more detail. Recent experimental evidences (see review [11]) hint at a whole series of surprisingly narrow states with masses and properties which, so-far, cannot be interpreted

consistently by theory.

Besides the spectroscopy of charmonium states, $\overline{\text{PANDA}}$ will also provide the capability to perform open-charm spectroscopy as the analog of the hydrogen atom in QED (heavy-light system). Striking discrepancies of recently discovered D_{sJ} states by BaBar [12] and CLEO [13] with model calculations have been observed. Precision measurements of the masses and widths of these states using antiprotons and by performing near-threshold scans are needed to shed light on these open problems.

2.2 Hybrids, glueballs, and other exotics

The self-coupling of gluons in strong QCD has an important consequence, namely that QCD predicts hadronic systems consisting of only gluons, glueballs, or bound systems of quark-antiquark pairs with a strong gluon component, hybrids. These systems cannot be categorized as "ordinary" hadrons containing valence $q\bar{q}$ or qqq . The additional degrees of freedom carried by gluons allow glueballs and hybrids to have spin-exotic quantum numbers, J^{PC} , that are forbidden for normal mesons and other fermion-antifermion systems. States with exotic quantum numbers provide the best opportunity to distinguish between gluonic hadrons and $q\bar{q}$ states. Exotic states with conventional quantum numbers can be identified by measuring an overpopulation of the meson spectrum and by comparing properties, like masses, quantum numbers, and decay channels, with - for instance - predictions from Lattice Quantum Chromodynamics (LQCD) calculations.

The first hints for gluonic hadrons came from antiproton annihilation experiments. Two particles, first seen in πN scattering with exotics $J^{PC}=1^{-+}$ quantum numbers, $\pi_1(1400)$ [14] and $\pi_1(1600)$ [15] are clearly seen in $\bar{p}p$ at rest and are considered as hybrid candidates. In the search for glueballs, a narrow state at 1500 MeV/c², discovered in antiproton annihilations by the Crystal Barrel collaboration [16–19] is considered the best candidate for the glueball ground state ($J^{PC}=0^{++}$). However, the mixing with nearby conventional scalar $q\bar{q}$ states makes a unique interpretation difficult.

The most promising energy range to discover unambiguously hybrid states and glueballs is in the region of 3-5 GeV/c², in which narrow states are expected to be superimposed on a structureless continuum. In this region, LQCD predicts an exotic 1^{-+} $\bar{c}c$ -hybrid state with a mass of 4.2-4.5 GeV/c² and a glueball state around 4.5 GeV/c² with an exotic quantum number of $J^{PC}=0^{+-}$ [20, 21]. The $\bar{p}p$ production cross section of these exotic states are similar to conventional states and in the order of 100 pb. All other states with ordinary quantum numbers are expected to have cross sections of about 1 μb .

2.3 Hadrons in the nuclear medium

One of the challenges in nuclear physics is to study the properties of hadrons and the modification of these properties when the hadron is embedded in a nuclear many-body system. Only recently it became experimentally evident that the properties of mesons, such as masses of π , K , and ω mesons, change in a dense environment [22–25]. The $\overline{\text{P}}\text{ANDA}$ experiment provides a unique possibility to extend these studies towards the heavy-quark sector by exploiting the $\overline{p}A$ reaction. For instance, an in-medium modification of the mass of the D meson would imply a modification of the energy threshold for the production of D mesons, compared to a free mass. In addition, a lowering of the D -meson mass could cause charmonium states which lie just below the $D\overline{D}$ threshold for the $\overline{p}p$ channel to reside above the threshold for the $\overline{p}A$ reaction. In such a case, the width of the charmonium state will drastically increase, which can experimentally be verified. Although this is intuitively a simple picture, in practice the situation is more complicated since the mass of various charmonium states might also change inside the nuclear medium.

Besides the indirect in-medium studies as described above, $\overline{\text{P}}\text{ANDA}$ will be capable to directly measure the in-medium spectral shape of charmonium states. This can be achieved by measuring the invariant mass of the di-lepton decay products. For the $\Psi(3770)$, for instance, models predict mass shifts of the order of -100 MeV [26], which are experimentally feasible to observe.

2.4 Hypernuclei

Nuclei in which one or more of the constituent nucleons are replaced by hyperons, hypernuclei, are promising laboratories to study the hyperon-nucleon and hyperon-hyperon interactions. Single and double Λ -hypernuclei were discovered 50 [27] and 40 [28] years ago, respectively, of which only 6 double Λ -hypernuclei are presently known. With a dedicated setup of $\overline{\text{P}}\text{ANDA}$ and its antiproton beam, a copious production of double Λ -hypernuclei is expected to be observed, providing a precision investigation of the Λ - Λ interaction. For this purpose, antiprotons at a moderate momentum of 3 GeV/c will interact with a primary target to produce large numbers of $\Xi\overline{\Xi}$ pairs. The $\Xi\overline{\Xi}$ decay provides a unique signature for the production. The corresponding Ξ particle will be stopped and captured in a secondary target. In case the Ξ is absorbed inside the nucleus, it will yield a Λ pair with very small (relative) energy. A (double) hypernucleus can be formed whose decay is observed with spectroscopic precision using Germanium detectors.

2.5 Other Topics

So far, this paper has concentrated on only a few of the topics which will be addressed by the $\overline{\text{PANDA}}$ collaboration. There exists, however, a large variety of other physics topics which can ideally be studied with the $\overline{\text{PANDA}}$ setup at the antiproton facility at FAIR.

In one of these “side” activities, symmetry violation experiments are being proposed which will open a window onto physics beyond the Standard Model of particle physics. This includes experimental studies of lepton flavor number violation using rare decay of D mesons and, in addition, CP violation studies by asymmetry measurements of $(D\overline{D})$ pairs near their production threshold in $\overline{p}p \rightarrow \Psi(3770) \rightarrow D\overline{D}$ and $\overline{p}p \rightarrow \Psi(4040) \rightarrow D\overline{D}$ reactions.

There is growing interest within the $\overline{\text{PANDA}}$ collaboration to make use of electro-magnetic probes, photons and leptons, in antiproton-proton annihilation. These probes will be used to study the structure of the proton by measuring Generalized Parton Distributions (GPDs), to determine quark distribution functions via Drell-Yan processes, and to obtain time-like electro-magnetic form factors by exploiting the $\overline{p}p \rightarrow e^+e^-$ reaction with an intermediate massive virtual photon. For example, estimates [29] of the count rates predict a few thousand $\gamma\gamma$ events per month for a luminosity of $2 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ at an energy of $\sqrt{s} = 3.2 \text{ GeV}/c^2$ for the crossed-channel Compton scattering process, which will be used to obtain GPDs. This indicates that such studies are feasible using beams of antiprotons together with a nearly- 4π electro-magnetic calorimeter, as foreseen with $\overline{\text{PANDA}}$.

3 The experimental facility

The $\overline{\text{PANDA}}$ detector will be installed at the High Energy Storage Ring, HESR, at the future Facility for Antiproton and Ion Research, FAIR. FAIR provides a storage ring for beams of phase-space cooled antiprotons with unprecedented quality and intensity [30]. Antiprotons will be transferred to the HESR where internal-target experiments in the beam momentum range of $1.5 - 15 \text{ GeV}/c$ can be performed. Electron and stochastic phase space cooling will be available to allow for experiments with either high momentum resolution of about $\sim 10^{-5}$ at reduced luminosity or with high luminosity up to $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ with an enlarged momentum spread of $\sim 10^{-4}$.

The $\overline{\text{PANDA}}$ detector is designed as a large acceptance multi-purpose setup. The experiment will use internal targets. It is conceived to use either pellets of frozen H_2 or cluster jet targets for the $\overline{p}p$ reactions, and wire targets for the $\overline{p}A$ reactions.

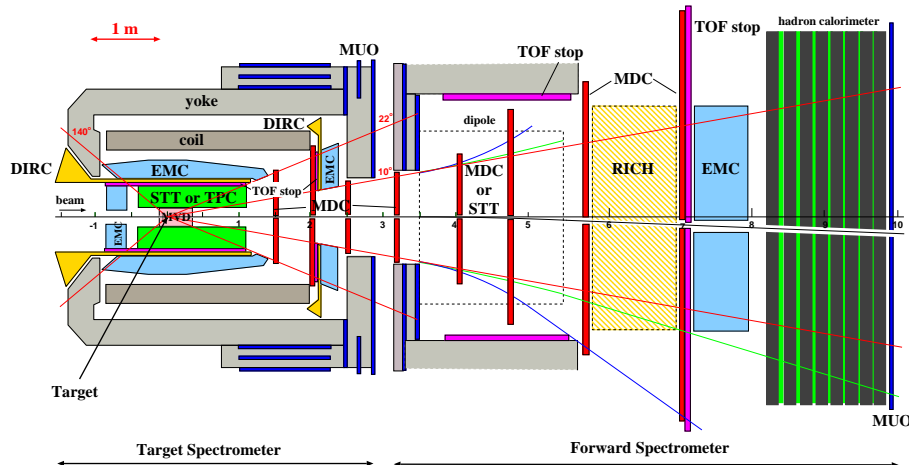


Figure 3: A schematic side view of the $\overline{\text{PANDA}}$ detector. The different components are abbreviated as DIRC (Detection of internally reflected Cherenkov photons), EMC (Electromagnetic calorimeter), STT (Straw-tube tracker), TPC (Time-projection chambers), MVD (Micro Vertex Detector), MDC (Mini drift chambers), MUO (Muon Detectors), RICH (Ring-imaging Cherenkov detectors), TOF (Time-of-flight detectors). Not shown are the recent plans to include Gas Electron Multipliers (GEMs).

In order to address the different physics topics, the detector needs to cope with a variety of final states and a large range of particle momenta and emission angles. At present, the detector is being designed to handle high rates of 10^7 annihilations/s, with good particle identification and momentum resolution for γ , e , μ , π , K , and p with the ability to measure D , K_S^0 , and Λ which decay at displaced vertices. Furthermore, the detector will have an almost 4π detection coverage both for charged particles and photons. This is an essential requirement for an unambiguous partial wave analysis [31] of resonance states. Various design studies are ongoing [32], partly making use of a dedicated computing framework for simulations and data analysis [33]. A schematic overview of the detector is given in Fig. 3.

4 Summary

The $\overline{\text{PANDA}}$ experiment at FAIR will address a wide range of topics in the field of QCD, of which only a small part could be presented in this paper. The physics program will be conducted by using beams of antiprotons together with a multi-purpose detection system, which enables experiments

with high luminosities and precision resolution. This combination provides unique possibilities to study hadron matter via precision spectroscopy of the charmonium system and the discovery of new hadronic matter, such as charmed hybrids or glueballs, as well as by measuring the properties of hadronic particles in dense environments. New insights in the structure of the proton will be obtained by exploiting electromagnetic probes. Furthermore, the next generation of hypernuclei spectroscopy will be conducted by the $\overline{\text{PANDA}}$ collaboration and at the J-PARC facility in Japan [34]. To summarize, $\overline{\text{PANDA}}$ has the ambition to provide valuable and new insights in the field of hadron physics which would bridge our present knowledge obtained in the field of perturbative QCD with that of non-perturbative QCD and nuclear structure.

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